π^0 rejection with POLfit in SK

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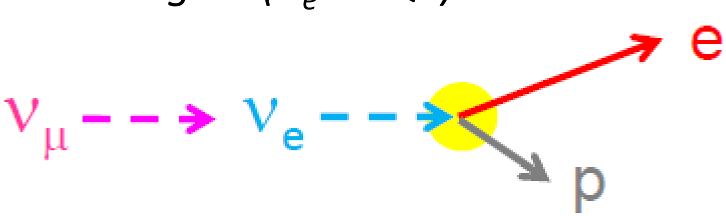
Introduction

- POL (Patten Of Light) fit
  - *Specialized event reconstruction tool to discriminate π^0 background from electron neutrino events using charge pattern of Cherenkov rings*
  - *Developed in Super-K atmospheric ν analysis, and also utilized in K2K/T2K ν_e search*
  - *Will explain algorithm and performance in this talk*
- Calibration of π^0 rejection efficiency in T2K
  - *hybrid-π^0 control sample*

What is π^0 background ?

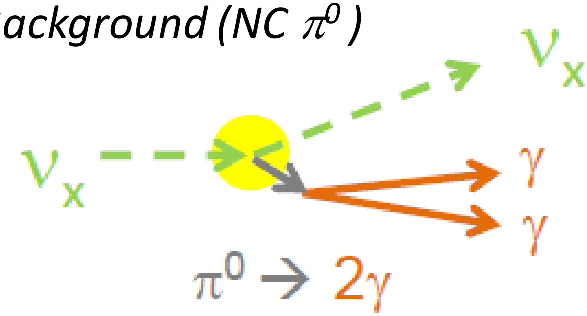
- Measurement of *CP violation* and *mass hierarchy* via $\nu_\mu \rightarrow \nu_e$ oscillation is one of motivations in Megaton WC detector
- Neutral-current induced π^0 is *most significant background* in ν_e oscillation analysis
- Could be ν_e CCQE signal-like if *2nd gamma ring is not identified*
  - *Reasons: smaller energy of 2nd gamma by asymmetric decay and overlapped rings*
  - *Both electron and gamma produce almost same charge pattern*

Signal (ν_e CCQE)



$\rightarrow$ Single-ring e-like event

Background (NC π^0)

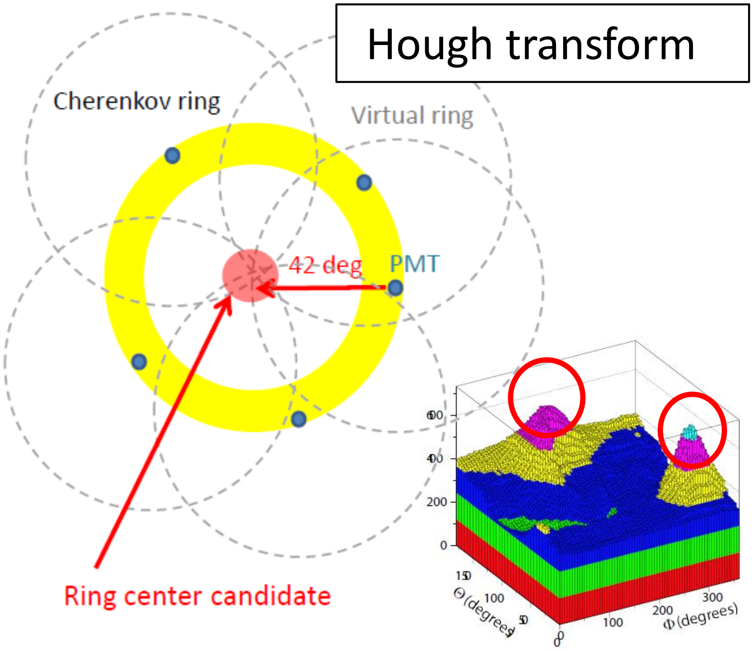


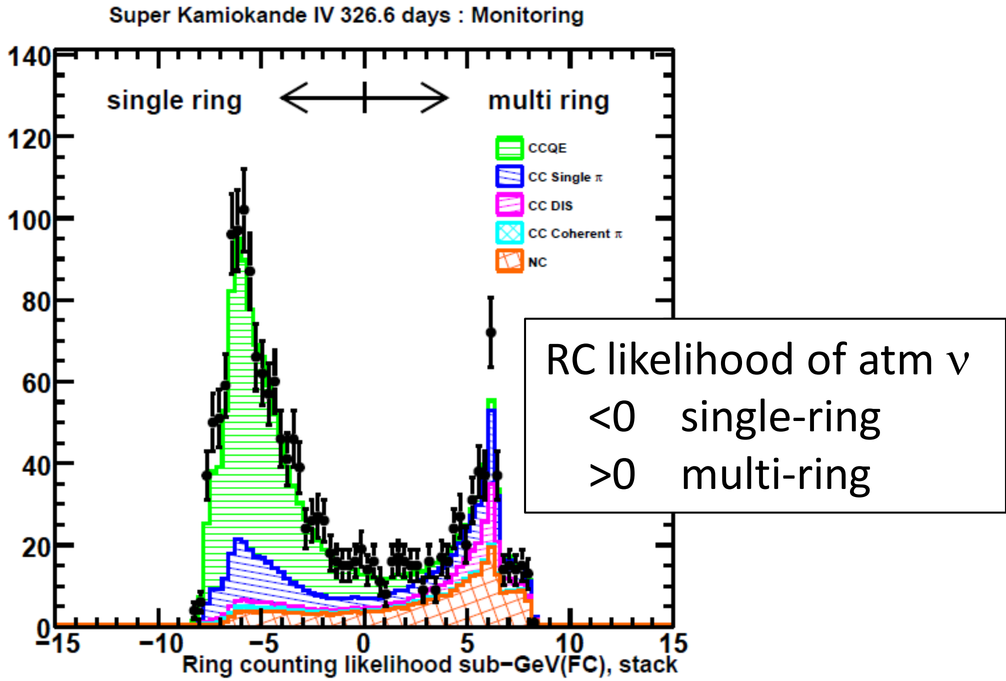
Purpose of POLfit

- *Force to find 2nd gamma ring* with two ring assumption
  - *Use charge pattern and likelihood method*
- Provide *kinematical variables* to identify π^0
  - *Reconstructed invariant mass*
  - *π^0 pattern likelihood*
- Reduce π^0 background events which cannot be identified by standard event reconstruction tool

Ring-counting in std. reconstruction

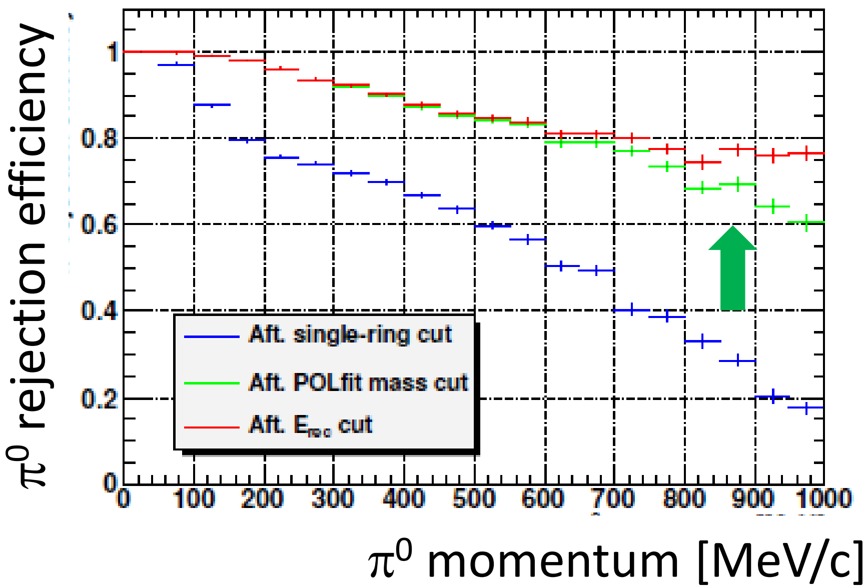
- Std. event reconstruction: vertex, ring-counting, PID, momentum
- Ring-counting provides *# of Cherenkov rings*
- Pickup ring candidates indicated by *Hough transform*, and test by *likelihood* method

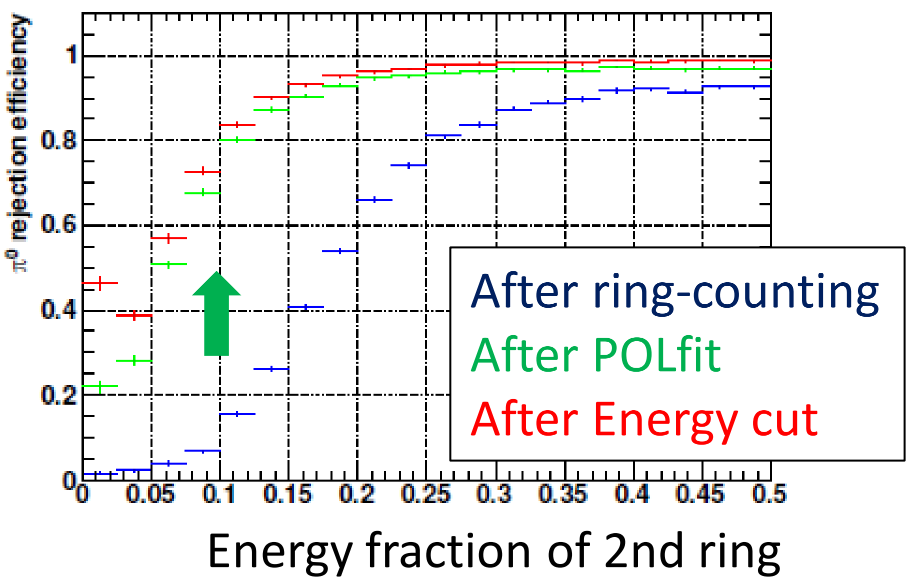




π^0 rejection by RC and POLfit

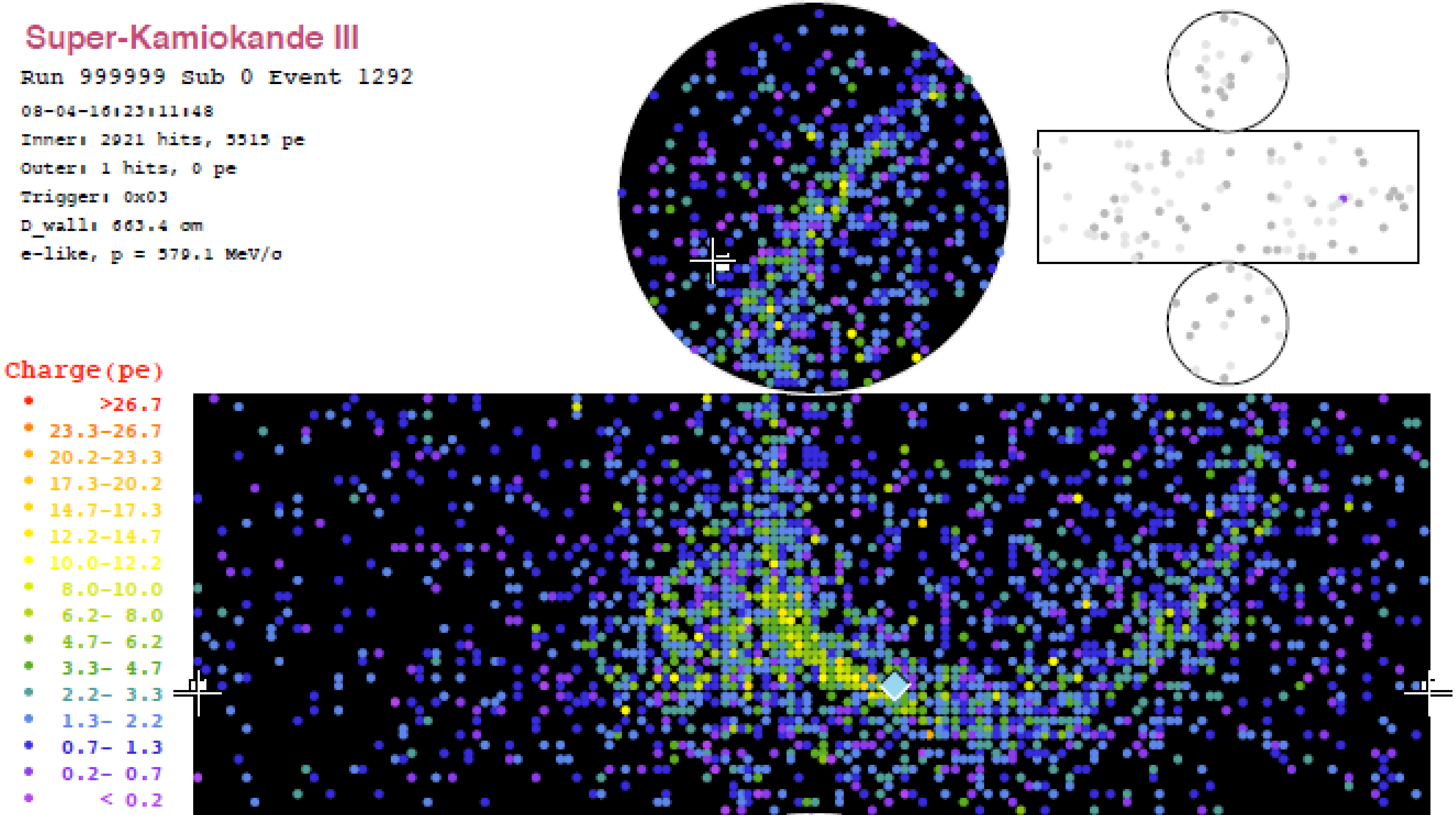
- POLfit can *significantly increase* π^0 rejection efficiency
  - *~80% → ~95% for $P(\pi^0)$ = 200 MeV/c*
  - *~60% → ~85% for $P(\pi^0)$ = 500 MeV/c*
- Also large improvement for *asymmetric-decay π^0* events having smaller 2nd ring energy

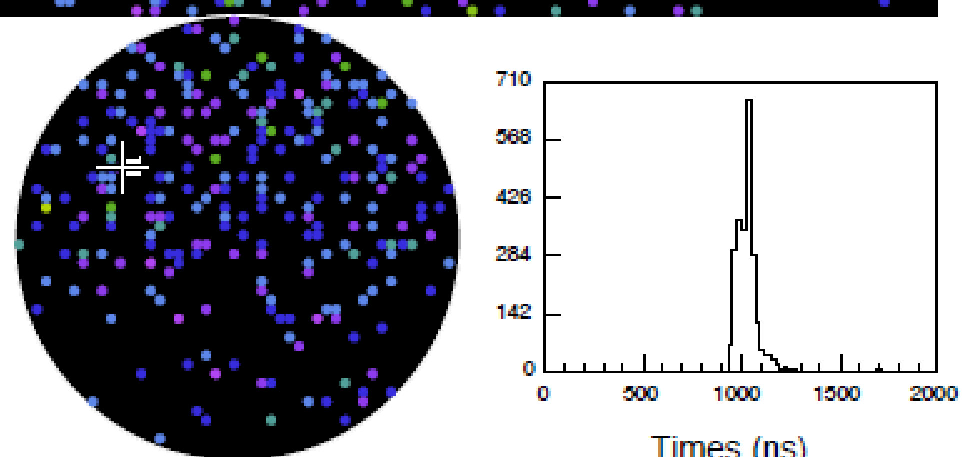


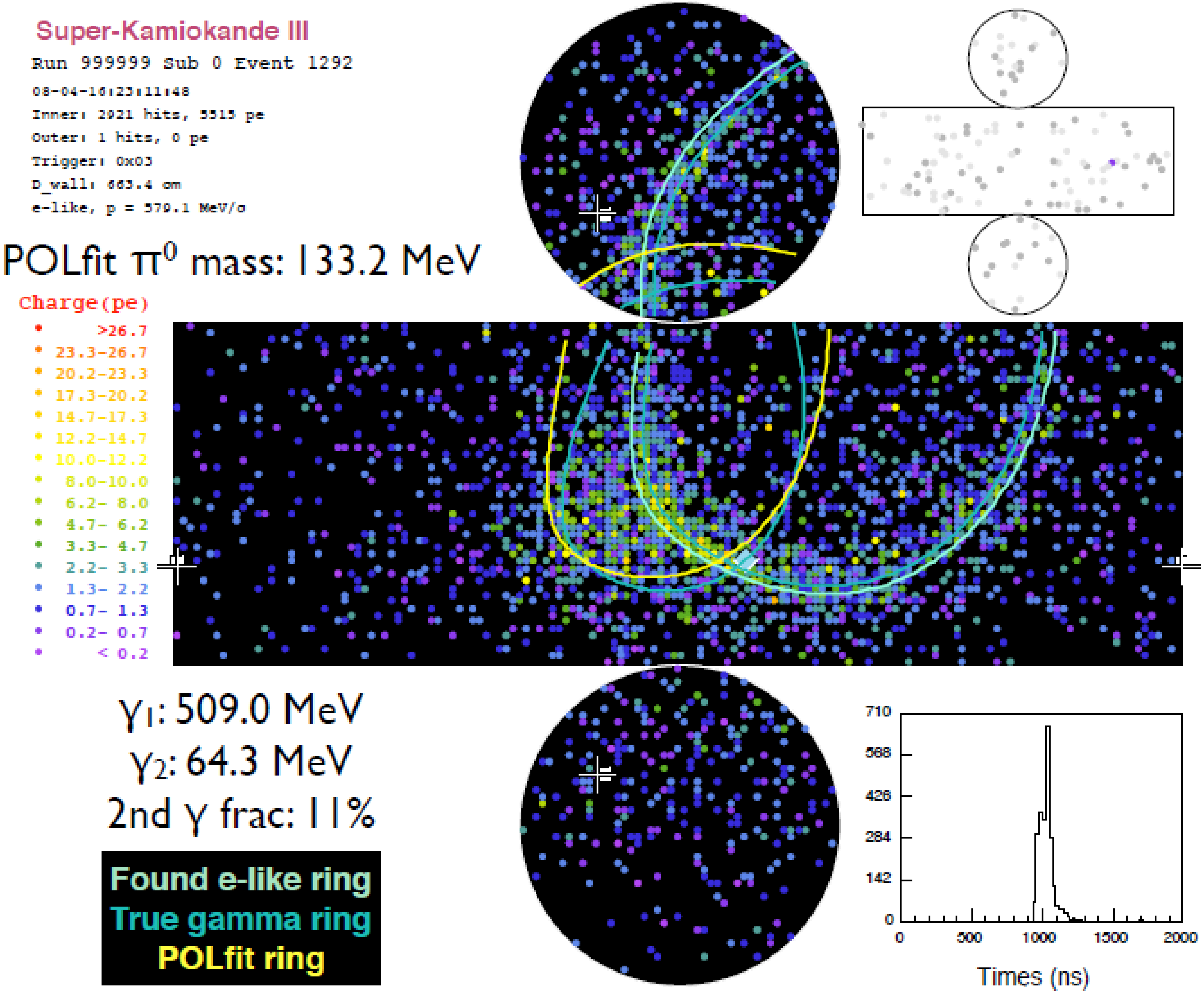


An Example

$$\nu + p \rightarrow \nu + p + \pi^0$$





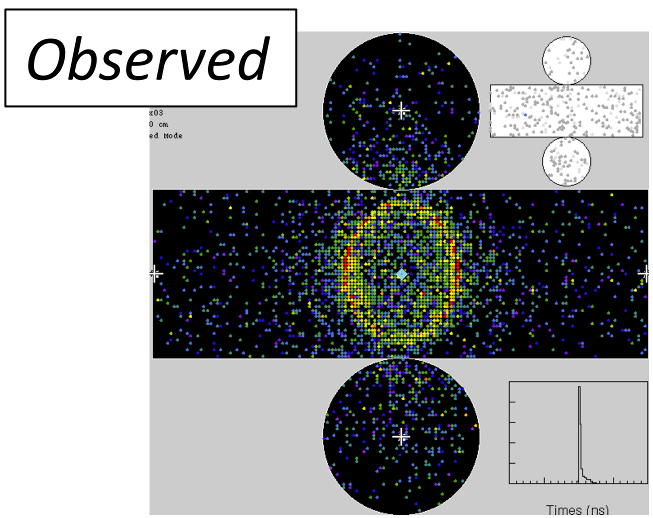

Super-Kamiokande III
Run 999999 Sub 0 Event 1292
08-04-16:23:11:48
Inner: 2921 hits, 5515 pe
Outer: 1 hits, 0 pe
Trigger: 0x03
D_wall: 663.4 cm
e-like, p = 579.1 MeV/c
POLfit π^0 mass: 133.2 MeV
Charge(pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
γ_1: 509.0 MeV
γ_2: 64.3 MeV
2nd γ frac: 11%
Found e-like ring
True gamma ring
POLfit ring
710
568
426
284
142
0
0
500
1000
1500
2000
Times (ns)

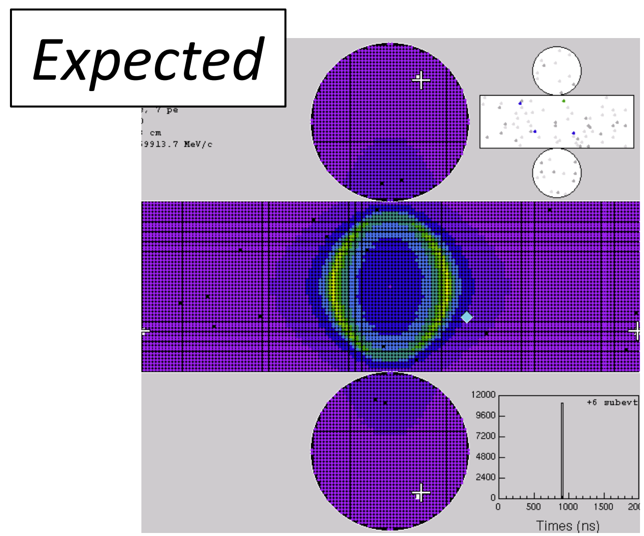
POLfit algorithm

1. INPUT: one found ring direction, vertex, and total charge (given by std. reconstruction)
2. Assuming there should be *two gamma rings*, search for a second ring
3. Assuming 2nd ring direction and energy, *generate expected light pattern* of 2-ring event.
4. *Compare* this pattern to observed. This is *iterated* until optimal 2nd ring location and energy are found.
5. Return π^0 *invariant mass* from optimal values
6. Also do comparison with 1R e-like assumption, and return *likelihood difference* between 1R e-like and 2R π^0-like.

Expected Cherenkov pattern

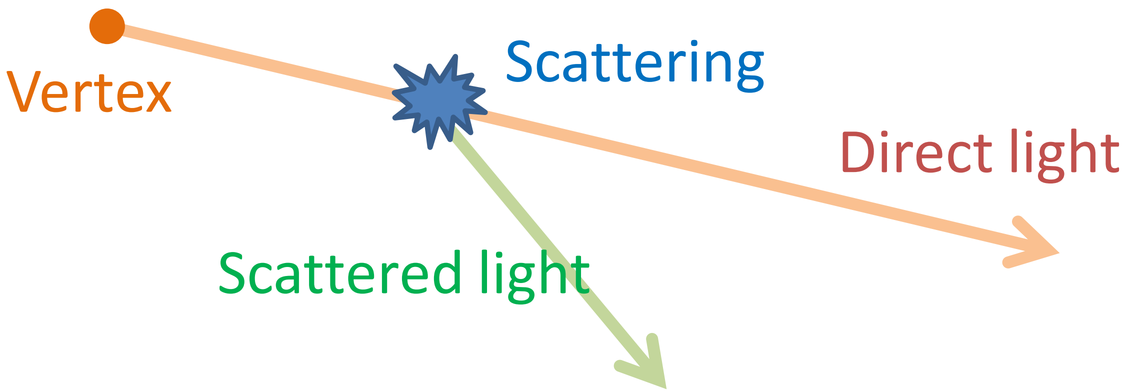
- Expected charge pattern can be generated with inputs of *vertex, direction, energy, particle-ID*
- Expected light consists of *direct light* and *scattered light*
- Direct light: *look up table* (generated from MC) by PID, momentum, distance to PMT, cosθ (Cherenkov opening angle)





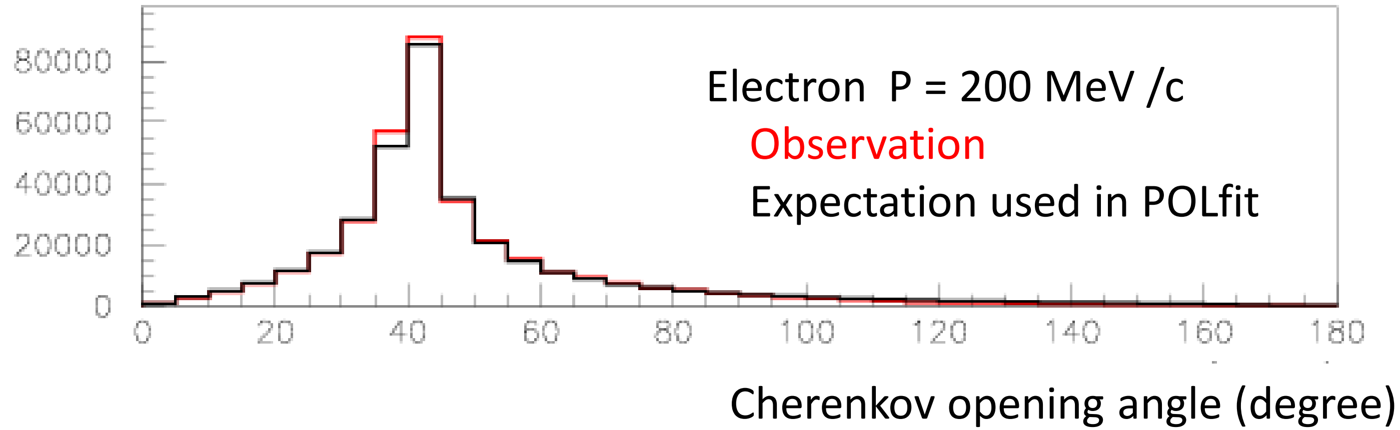
Scattering light calculation

- Along a path of direct light from vertex, scattering is calculated and its amount is integrated
- This integration is done for all direct light directions
- Attenuation in water and scattering angle are considered
- Calculation is based on coarse "patch" group



Expected light: Comparison with observation

- Some correction are made for *solid angle of PMT*
- After adding direct and scattered lights, expected charge is *normalized to observed charge*
- Angle distributions between observation and expectation *well agree*

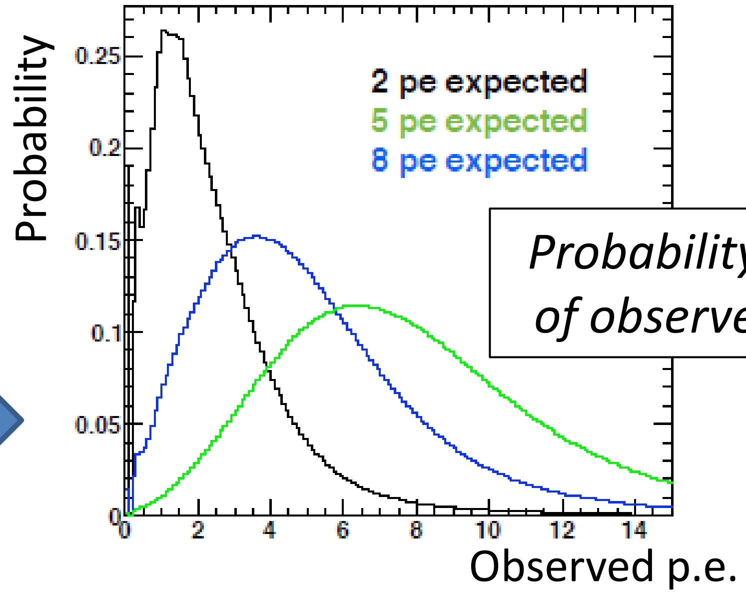


POLfit Likelihood

- For each expected light pattern, a *likelihood* is generated by comparing that pattern to the observed pattern.
- *Probability function* based on measured single photo electron distribution of real PMT is used
- This likelihood function is fed into *MINUIT minimizer*

Likelihood :

$$\mathscr{L} = \sum_{PMT} \ln \underline{\mathrm{Prob}(Q_{\exp}, Q_{obs})}$$

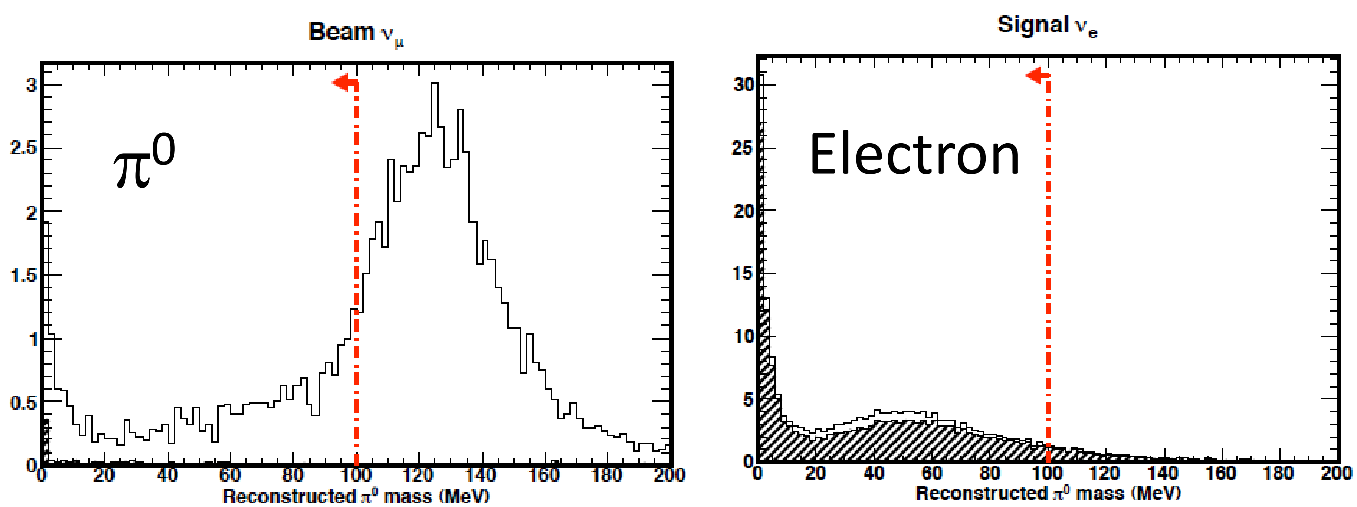


Probability function of observed charge

POLfit output

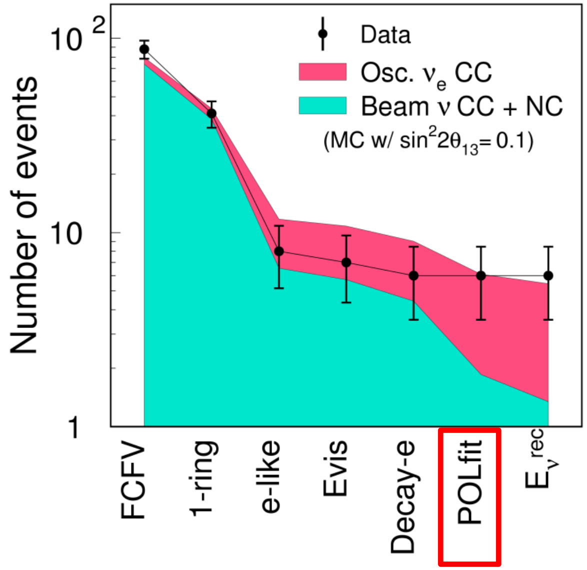
- After minimization, *momentum of both two rings* and *2nd gamma direction* are obtained
- *Invariant mass* is constructed using this output. This is used as discrimination parameter between electron and π^0
- Backgrounds have a peak around π^0 mass (~135MeV). Can reject them by <~100 MeV/c cut.

Reconstructed invariant mass by POLfit

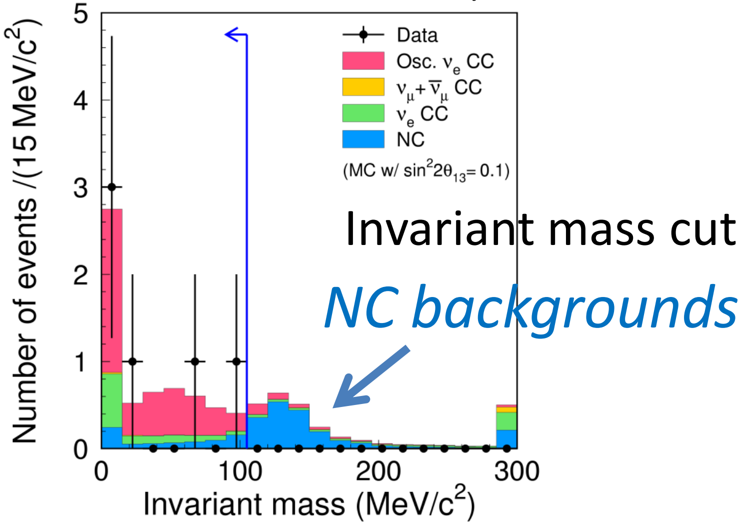


POLfit performance in T2K analysis

- Invariant mass cut is applied after 1-R e-like selection
  - *Optimize cut criteria by MC : $M_{inv} < 105$ MeV/c^2*
- *Significant reduction* for NC backgrounds
  - *~95% π^0 rejection, 66% signal acceptance achieved by all cuts*
- NC π^0 is no more most significant background
  - *amount of NC BG is less than beam intrinsic ν_e in T2K*



T2K RUN1+2 analysis

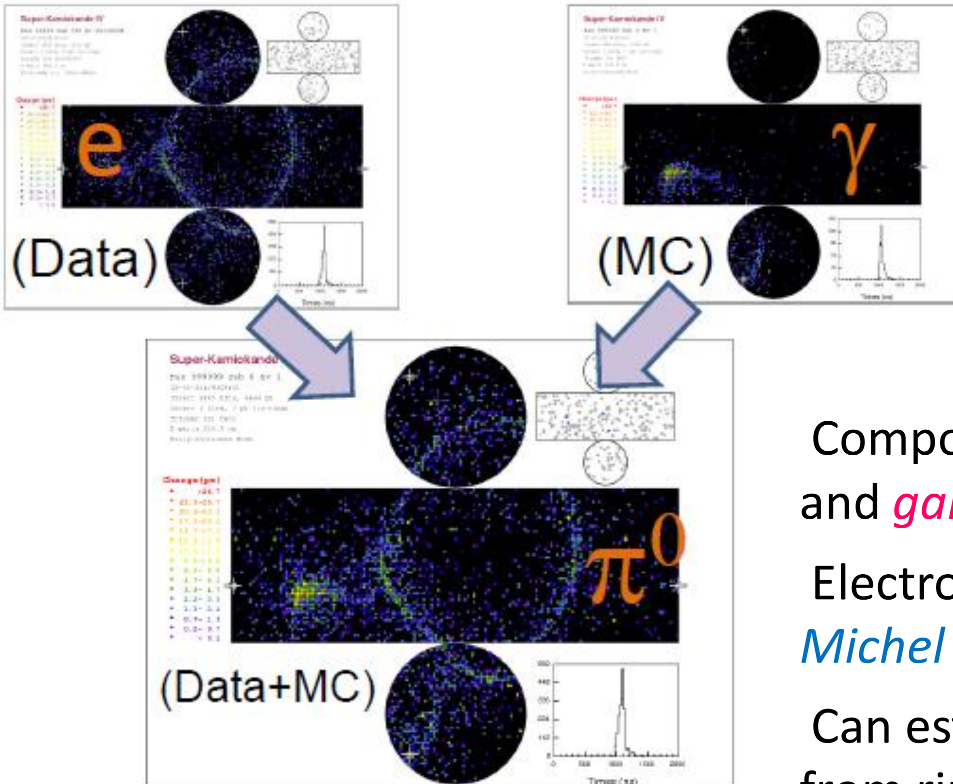


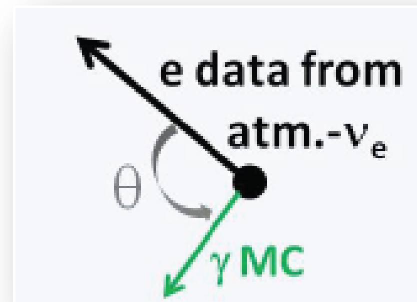
Calibration of π^0 efficiency (hybrid- π^0 sample)

Calibration of π^0 rej. efficnecy

- *Need to verify/confirm* POLfit performance and estimate systematic error of π^0 background
- There are *many possible syst. error sources*
  - *Any component affecting charge pattern could be error source*
  - *EM shower simulation, Cherenkov light emission, scattering/absorption in water, reflection on PMT surface, PMT QE, gain, electronics, etc.*
- Difficult to control all these uncertainties by MC-based study
- Solution: *Control sample* based study using data
  - *Data/MC difference includes all these uncertainties*
  - *But we don't have π^0 calibration data ...*

Hybrid-π^0





Composite event sample with *electron data* and *gamma MC*

Electrons are taken from *atm.* ν and *cosmic Michel electron*

Can estimate *systematic uncertainty* coming from ring where electron is used

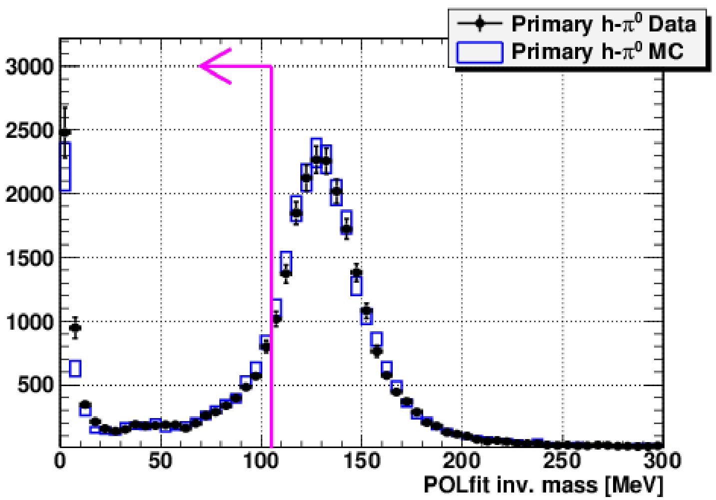
Apply T2K ν_e selection and *compare cut efficiency* between control sample data and its MC

Hybrid-π^0: Generation

- Produce with *same kinematics* (energy, dir.) as T2K's π^0
  - *Pick up a NC $\pi^0 \rightarrow 2\gamma$ vectors from T2K MC, and choose electron event which energy is close to one gamma vector*
  - *Allow to rotate vector coordinate around SK detector axis in order to match opening angle from beam dir.*
  - *Generate gamma MC with electron's vertex. Direction and energy are taken from another gamma vector in rotated coordinate*
  - *Combine electron event and gamma MC*
- Data/MC sample
  - *(e data) + (γ MC) $\leftrightarrow$ (e MC) + (γ MC)*
  - *Selection efficiency difference $\rightarrow$ systematic error*
- *Primary* and *secondary* sample
  - *Need to estimate uncertainties coming from both rings*
  - *Primary: use electron for higher energy ring, secondary: lower ring*

Hybrid-π^0: Result

Invariant mass of h-π^0 Data/MC



Data/MC diff. after cut selection:

7.8 % in primary sample

4.3 % in secondary sample

by taking quad. sum, 10.8% error estimated for amount of π^0 BG (considering stat. uncertainty of sample)

Far detector (SK) systematics in T2K ν_e analysis

Error source	$\frac{\delta N^{MC}_{SK\ \nu_e\ sig.}}{N^{MC}_{SK\ \nu_e\ sig.}}$	$\frac{\delta N^{MC}_{SK\ bkg.\ tot.}}{N^{MC}_{SK\ bkg.\ tot.}}$
π^0 rejection	-	3.6%
Ring counting	3.9%	8.3%
Electron PID	3.8%	8.0%
Invariant mass cut	5.1%	8.7%
Fiducial volume cut etc.	1.4%	1.4%
Energy scale	0.4%	1.1%
Decay electron finding	0.1%	0.3%
Muon PID	-	1.0%
Total	7.6%	15%

In total background (intrinsic ν_e, NC, others), 3.6% uncertainty is estimated from π^0 rejection efficiency

Summary

- We have been studying π^0 backgrounds for precise measurement of $\nu_\mu \rightarrow \nu_e$ oscillation
- POLfit is a powerful tool for π^0 background rejection in ν_e appearance search
  - *Optimal 2nd ring direction is searched by Likelihood method comparing with expected light pattern*
  - *Reconstructed invariant mass is used as a discrimination parameter between electron and π^0*
  - *Significant improvement after standard ring-counting tool*
- Developed new control sample for π^0 efficiency calibration (hybrid- π^0)
  - *Composite event with electron data and gamma MC*
  - *Estimate ~11% systematic error on π^0 background*